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Superconducting Triple-Spoke Cavity for β=0.5 Ions*

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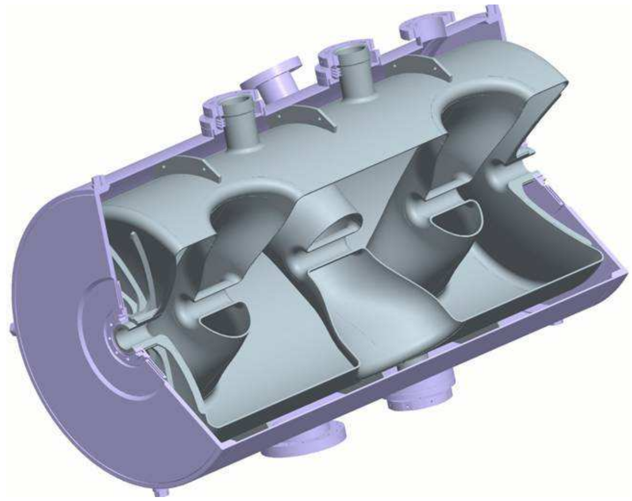

Figure 1: Cut-away view of the niobium triple-spoke cavity nested in an integral stainless-steel helium vessel 83 cm in length. Some of the mechanical support ribs welded to the exterior niobium shell are visible.

U.S.A.

Abstract

This paper reports results of cold tests of a 345 MHz, three-spoke-loaded TEM-class superconducting niobium cavity being developed for the RIA driver linac and for other high-intensity ion linac applications. The cavity has a beam aperture of 4 cm diameter, an interior length of 67 cm, and the transit-time factor peaks at $\beta = v/c = 0.5$. In tests at 4.2 k, the cavity could be operated cw above the nominal design accelerating gradient of 9.9 MV/m, which corresponds to peak surface fields of 27.5 MV/m electric and 850 gauss magnetic. At this gradient the cavity provides more than 6 MV of accelerating potential. Cavity Q at 9.3 MV/m exceeded the nominal performance goal of 7.3×10^8. Operation at the design gradient at 4.2 K causes substantial boiling and two-phase flow in the liquid helium coolant, with the potential for microphonic-induced fluctuations of the rf frequency. Total micro-phonic rf frequency fluctuations were less than 1 Hz RMS operating cw at 9.7 MV/m at 4.2 K

INTRODUCTION

Superconducting, TEM-class, 345 MHz spoke-loaded cavities are being developed for the high-energy section of the driver linac for the proposed U. S. rare-isotope accelerator facility (RIA) and other ion-linac applications [1,2]. Spoke-loaded cavities enable operation at lower frequency than is practical with elliptical-cell cavities and, in the case of the multi-beam RIA driver linac, offer an attractive alternative to 805 MHz elliptical-cell cavities such as have been developed for the SNS proton linac.

As was discussed in a previous paper [2], the lower operating frequency possible with spoke cavities leads to several operational advantages:

- Longer cell length, providing more voltage per cavity and/or broader velocity acceptance.
- Increased longitudinal acceptance, reducing beam loss and increasing alignment and control tolerances.
- Lower surface resistance, enabling operation at 4.2 K

The aim of the work presented here is to demonstrate the feasibility of using spoke cavities for the high energy section of the RIA driver linac by cold-testing prototype niobium cavities. We discuss below the design, construction, and cold-tests of a three-spoke-loaded cavity for particle velocities $\beta \cong 0.5$.

DESIGN AND CONSTRUCTION

Figure 1 shows a sectioned view of the three-spoke-loaded cavity. The niobium cavity shell is contained in an integral stainless-steel (SS) helium jacket with an overall length of 83 cm, and an OD of 47 cm. Two 2-inch diameter coupling ports and a helium port can be seen at the top of the cavity. Also visible are several of the niobium ribs welded to the exterior of the niobium shell for mechanical stiffening. The SS jacket is joined to the niobium shell at the beam ports and at the coupling ports using a coaxial braze joint made with pure copper in a vacuum furnace[4].

Cavity Design

The design was constrained to provide a 345 MHz three-spoke-loaded cavity of $\beta_{GEOM} = 0.5$ with a 4 cm beam aperture. The design priorities were to minimize the peak surface electric and magnetic field and to provide good mechanical stability. The electromagnetic properties were numerically modeled using CST Microwave Studio, Version 5. The mechanical properties were modeled using Pro-E and ANSYS.

Table I: Electromagnetic properties of the cavity

Frequency	**345 MHz**
β_{GEOM}	**0.50**
L(3$\beta\lambda$/2)	**65.2 cm**
QRs (G)	**88.5 Ω**
R/Q	**492 Ω**
below for E_{ACC} = 1.0 MV/m	
RF Energy	**0.398 J**
B_{PEAK}	**86 G**
E_{PEAK}	**2.79 MV/m**

The three lowest frequency rf eigenmodes of the cavity are TEM-like modes with each spoke excited as a half-wave line. The accelerating rf eigenmode is the lowest frequency mode, in which adjacent spokes differ in phase by π radians.

The spoke elements are elliptical in cross section in order to minimize the peak surface fields while accommodating a 4 cm beam aperture. The major axis of the ellipse is normal to the beam axis in the center of each spoke to minimize the surface electric field and maximize the beam aperture. The major axis is parallel to the beam axis in the region of the spokes near the outer cylindrical diameter of the cavity in order to minimize the peak surface magnetic field.

Table I details the electromagnetic properties for the accelerating rf eigenmode. The accelerating gradient E_{ACC} in Table I is referenced to an effective length l_{eff} = 62 cm, where we have followed the suggestion of Delayen [5] in taking $l_{eff} = n \cdot \beta_{GEOM} \cdot \lambda/2$, where n is the number of spokes, λ the free-space wavelength at the frequency of the accelerating mode, and β_{GEOM} the reduced velocity at the peak of the transit-time function.

Mechanical Design

The niobium cavity shell is formed of 1/8 inch sheet which deforms appreciably from the ambient pressure of the helium coolant at 4.2 K. The deformation shifts the rf frequency of the cavity, so that pressure fluctuations in the liquid helium bath can cause microphonic phase noise.

To minimize problems with phase-control, the cavity has been designed to minimize the shift in frequency caused by helium pressure change (df/dp). As can be seen in Figure 1, mechanical support ribs have been added both to the end walls and also to the cylindrical wall of the cavity. These ribs stiffen the cavity and reduce the wall displacement caused by pressure of the helium bath.

It is not practical, however, to stiffen the cavity sufficiently to reduce df/dp to a tolerably small value. For example, at 1 atmosphere pressure, the radial inward displacement of the cylindrical portion of the cavity wall, where the rf surface fields are primarily magnetic rather than electric, causes the rf frequency to increase on the order of 100 kHz, even with the stiffening gussets in place. Note, however, that the total rf frequency shift also includes a decreasing term associated with an inward displacement of the dished end-walls, where the surface electric field predominates.

We have minimized the net frequency shift by tailoring the design of the support ribs to make the two terms cancel, using numerical finite element analysis (FEA) to size and place the ribs. Some of the ribs were made slightly oversize, leaving an estimated residual df/dp = -8 kHz/atm. This was done to allow a final, post-construction tuning by cutting away part of the support gussets after measuring the actual df/dp at 4K.

Construction

Except for the beam ports, which were machined from bar stock, all niobium elements were formed from 1/8 inch sheet. All niobium was characterized by a residual resistivity ratio RRR > 250. The cavity spherical end-walls and the spoke elements were hydro-formed. The spokes were formed in halves and seam welded together. Transition rings were formed and welded to the ends of the spokes to provide a transition to the cylindrical housing with a blend radius of ½ inch.

All welds were electron beam (EB) welds performed at pressures below 10^{-5} torr, and the joined parts were cooled in vacuum below 50C before venting the welding chamber.

Tuning and Electropolishing

Tuning and preliminary surface processing were performed when the three major sub-assemblies of the cavity were complete: namely, the two spherical end-walls, complete with beam ports and support ribs, and the body of the cavity with coupling ports and all three spokes welded into the cylindrical housing.

Tuning was accomplished by clamping the three sections together, using a thin layer of indium to join the sections, and the rf eigenfrequency was measured. The frequency was then brought to design value by machining to adjust the spacing between the end walls and spoke elements.

Prior to welding the three sections together, each was heavily electropolished, removing 150 – 200 microns of material to eliminate any damage caused by forming and machining. After EB welding the three niobium sections together, the SS helium jacket was clam-shelled into place and welded together. The niobium-SS braze transitions

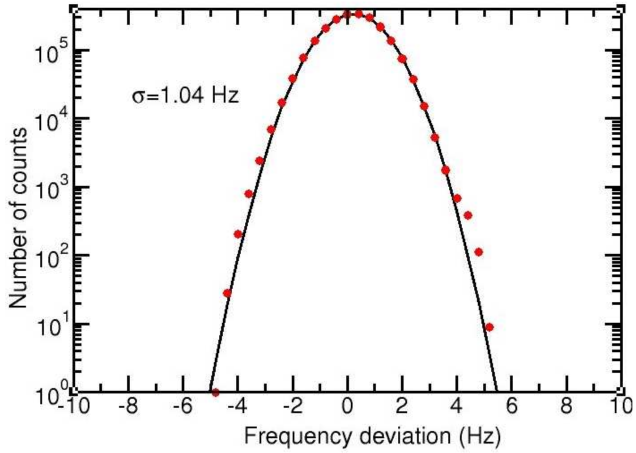

Figure 3: Distribution of frequency errors measured at E_{ACC}=9.7 MV/m. The distribution is Gaussian over 5 orders of magnitude, with an RMS fluctuation of 1.1 Hz.

were then EB welded to the niobium shell to complete the assembly.

PROCESSING AND COLD TESTS

The completed cavity was given a light (4-7 micron) buffered chemical polish (BCP). BCP was performed through the 2 inch ID coupling ports with the cavity in a horizontal position. It was found that a bubble could cling to an area roughly 10 cm in diameter at top of the housing, possibly preventing full chemical polishing of this portion of the surface. To ensure a complete BCP, the cavity was rotated 180 degrees and given a second 4-7 micron BCP.

Upon cooling, the performance shown in Figure 2 was measured. The cavity could be operated cw at accelerating gradients up to 10.2 MV/m. At the nominal design gradient of 9.9 MV/m the rf loss at 4.2 K was 95 watts, corresponding to 14.7 watts per MV of accelerating potential.

Mechanical properties and microphonics

The Lorenz detuning was measured to be 7.3 Hz per $(MV/m)^2$. The shift of rf frequency caused by changing the pressure of helium in the cooling jacket was found to be -9.6 kHz/atm, very close to the value of -8 kHz/atm predicted by FEA analysis of the design [6].

Because of the relatively small beam-loading of the RIA driver linac, the mechanical stability and microphonic behavior of the SC cavities are particularly critical. In operation at 4.2K the rf loss causes substantial boiling in the liquid helium with the potential of causing microphonic fluctuations in pressure and rf eigenfrequency.

Microphonic frequency fluctuations were measured at 4.2K with the cavity operating at E_{ACC}=9.7 MV/m. The results are shown in Figures 3 and 4.

As shown in Figure 3, the magnitude of the microphonics is sufficiently small, 1 Hz RMS, that a tuning window of a few tens of Herz would be adequate for phase-control.

Figure 4 shows that microphonics causing significant phase error (>0.3°) occur only at low frequency, so that a mechanical fast tuner may be practical for this cavity. Also shown in Figure 4 are lines at 60 and 120 Hz which are due to phase noise in the reference oscillator, which contributes a significant fraction of the observed 1 Hz rms microphonic amplitude.

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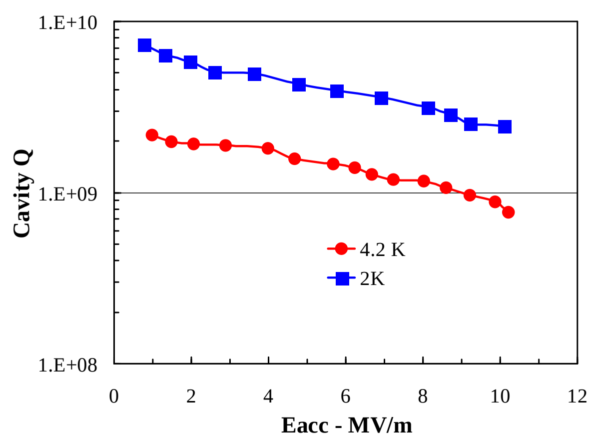

Figure 2: Cavity Q as a function of accelerating gradient

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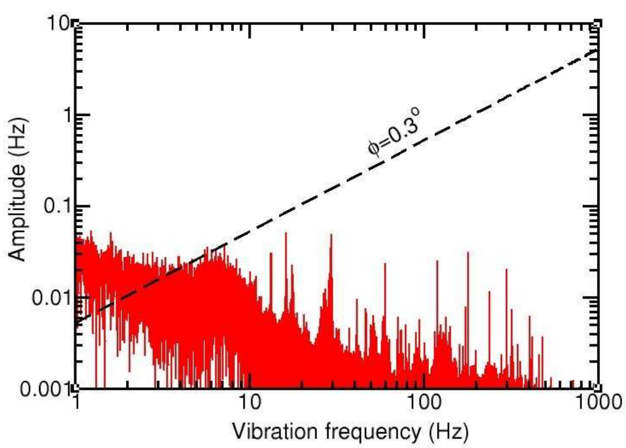

Figure 4: Frequency spectrum of microphonic fluctuations of the rf eigenfrequency of the triple spoke cavity at 9.7 MV/m and 4.2K.